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PHYSIOLOGICAL EFFICACY OF A LIGHTWEIGHT AMBIENT AIR COOLING UNIT FOR VARIOUS APPLICATIONS

Yasu Tai Chen
Susan H. Bomalaski
Stefan H. Constable

CREW SYSTEMS DIRECTORATE
CREW TECHNOLOGY DIVISION
2504 D Drive, Suite 1
Brooks Air Force Base, TX 78235-5104

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The voluntary, fully informed consent of the subjects used in this research was obtained as required by AFR 169-6.

The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

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YASU TAI CHEN, M.S., P.E.
Project Scientist

William F. Storm

WILLIAM F. STORM, Ph.D.
Chief, Sustained Operations Branch

RICHARD L. MILLER, Ph.D.
Chief, Crew Technology Division

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Yasu Tai Chen
Susan H. Bomalaski
Stefan H. Constable

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Armstrong Laboratory (AFMC)
Crew Systems Directorate
Crew Technology Division
2504 D Dr. Ste 1
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13. ABSTRACT (*Maximum 200 words*)
In an attempt to further advance intermittent conditioned air cooling (IC) concept, a strategy of supplementing continuous air cooling (CC) was conceived. With this approach, ambient air cooling (AC) is added during work with conditioned air cooling delivered during rest periods. A compact, battery-powered beltpack cooling unit (8.5 lb), designed and fabricated at the USAF Armstrong Laboratory, was used to deliver 12 cfm filtered ambient air during work cycles: 10 cfm to the body and 2 cfm to the face.
Five experimental trials were completed in a thermally controlled chamber under warm conditions (32°C, 40% RH) consisting of no cooling (NC), IC, and CC during intermittent exercise, as well as NC and AC during continuous exercise.
This study suggests that ambient air delivered during work by a lightweight portable unit can be applied in conjunction with conditioned air during rest to further improve personal comfort, reduce skin temperature, and decrease the cumulative fatigue seen over repeated work/rest cycles in selected military and industrial applications.

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PHYSIOLOGICAL EFFICACY OF A LIGHTWEIGHT AMBIENT AIR COOLING UNIT FOR VARIOUS APPLICATIONS

INTRODUCTION

Thermal stress to personnel wearing protective equipment and working in warm, potentially contaminated environments is a critical problem in industry and the armed forces. While performing under such stressful conditions, an individual might wear a protective garment such as the U.S. Armed Forces chemical defense ensemble (CDE) that features high thermal insulation and low moisture permeability (6). The physiological impact from exposure to stressful environmental and metabolic heat loads are increased body heat storage, decreased work performance, and possible physical injury (4).

During the past decade, various personal microclimate liquid and air cooling systems have been developed and studied (8, 9). These personal cooling approaches accelerate the removal of stored heat and, therefore, reduce body core temperature. However, human-mounted cooling units normally have the disadvantage of increased weight carriage, movement encumbrance, and often only modest physiological cooling capacity (5). The use of an air- or water-cooled stationary system during work cycles by tethering the supplying lines to subjects has improved task performance and personal comfort in certain industry settings (1).

Most U.S. Air Force (USAF) ground crew cannot perform their duties if they are tethered to a stationary cooling facility; therefore, the concept of intermittent microclimate cooling during rest periods only has been investigated (2). Use of either air or liquid upper-body cooling during scheduled rest periods lengthened work times, lessened the associated physiological stress, and improved personal comfort compared with control, no cooling trials. However, even though cumulative heat storage was prevented, general physical fatigue was still more progressive than it was when no CDE was worn (3). Therefore, this approach was considered only a partial, near-term solution.

To further improve this more limited concept, a strategy of implementing continuous air cooling with the added wear of an ambient air blower was conceived. With this approach, filtered, ambient air cooling is added during work cycles while conditioned air cooling is delivered via a multiman system during the requisite rest periods. Therefore, a lightweight ambient air cooling unit which can provide adequate clean air was developed and tested in a controlled thermal chamber. This report describes the development and testing of the lightweight, human-mounted air cooling approach.

METHODS

System Description

A prototype ambient air cooling unit was designed and fabricated at the USAF Armstrong Laboratory, Brooks Air Force Base, Texas. The cooling unit is composed of a direct current (DC) vacuum blower, battery set, air plenum, control panel, three Army C-2 filters, and a support frame (Fig 1). This compact "belt pack" unit, weighing approximately 8.5 lbs (4 kg) with battery, provides 12 cfm filtered ambient air through a U.S. Army developed air vest (7): 10 cfm to the body and 2 cfm to the face. The unit, energized by a 2.2-amp, 24 VDC, battery activates a one-stage blower that draws ambient air through three canister filters for up to 3 h of continuous operation.

Commercial off-the-shelf industrial respirator products for use in hazardous areas were evaluated for possible USAF ground crew use. None of the available products would meet the requirements for providing the specified air volume (12 cfm) at a high resistance (6 in./15.24 cm H_2O). However, most major components can be obtained "off the industry shelf," making this prototype system relatively simple and inexpensive to build. Also, the unit is ergonomically balanced on the individual's hips with shoulder supports; it does not appear to interfere with normal job performance (Fig. 2). The unit may be used independently or in conjunction with the multiman intermittent cooling system (MICS) approach, also developed by the environmental stress/fatigue group at the USAF Armstrong Laboratory. The lightweight unit does not overburden the user; a heavy unit would obviously affect its cooling capacity during work periods.

Human Testing

The seven subjects used for the series of tests were military volunteers, 20 to 27 years old, 5 ft 9 in. (175.3 cm) to 6 ft 3 in. (190.5 cm) tall, and weighed 165 lb (75 kg) to 200 lb (90.0 kg). All subjects were active duty military personnel assigned to Brooks Air Force Base.

Subjects wore the Army air vest over a cotton T-shirt, under the battle dress uniform (BDU). Over the BDU they wore the military CDE including jacket, pants, rubber gloves, with cotton liners, and an MCU-2/P mask with a hood and C-2 filter. Tennis shoes rather than chemical protective overboots were worn for comfort and to prevent injury.

The physical task used for all test batteries in this study consisted of treadmill walking at 3 mph (4.8 kph) on a 3-6% grade, which elicited approximately 40% of subjects' max VO_2.

Subjects performed either intermittent or continuous exercise in a thermally controlled chamber under warm, (90°F [32°C]/40% RH) until rectal temperature (T_{re}) measured 102.2°F (39.0°C), heart rate (HR) measured 180 bpm, or until they reached volitional fatigue limits.

For intermittent work, three experimental conditions were used (subjects served as their own controls): (1) No Cooling (NC)--subjects completed the intermittent exercise periods without any personal cooling during work or rest cycles; (2) Intermittent Cooling (IC)--subjects received conditioned air cooling during rest periods, but walked on the treadmill without ambient air cooling; and (3) Continuous Cooling (CC)--subjects wore the ambient air cooling unit during work periods and received conditioned air cooling during rest periods. In this intermittent work scenario, four cycles of 40-min work (450 W or 387 Kcal/hour) and 20-min rest were attempted at each condition.

Subjects received 18 cfm of conditioned air (60-65°F/15.5°C-18.3°C) during 20 min of rest for the IC and CC conditions. Fifteen cfm was pumped to the body through the Army aircooled vest and 3 cfm was supplied to the face through the C-2 filter. Air temperature and airflow were monitored and maintained at constant levels. Subjects were allowed to drink cool water during rest periods in any experimental condition; the amount of water they drank was recorded.

In a second set of experiments during continuous work, subjects walked on the treadmill continuously until they reached one of the termination criteria specified earlier. Two experimental conditions were observed: (1) No Personal Cooling (NC)--subjects did not carry an ambient air cooling unit; therefore, no ambient air was delivered to the body during exercise. (2) Ambient Air Cooling (AC)--subjects carried an air unit without cooling on the hip and received 12 cfm ambient air during exercise.

Data Collection and Analysis

Rectal (T_{re}) and mean skin (T_{sk}: forearm, chest, thigh, calf) temperatures, along with HR, were continuously monitored and recorded via a computer data acquisition system. Sweat production and sweat loss (evaporation) rates were calculated from pre- and post-experiment nude and clothed body weights. Subjective values of rated perceived exertion (RPE) and thermal comfort (TC) were taken every 10 min.

Statistical analysis using a 3-way analysis of variance (ANOVA) was conducted using physiological data and ratings from TC and RPE from all these conditions, and a second 3-way ANOVA, was used to specifically compare IC and CC using paired data from

these conditions only. Rates of sweat production (PROD) and evaporation (EVAP) were analyzed using a 2-way ANOVA. Significance was accepted at the P=0.05 level for all tests. Duncan's Multiple Range Test was used to identify specific mean differences.

RESULTS

During the intermittent work scenario where they attempted 4-h work/rest cycles, all seven subjects completed at least 80 min in the NC trial. Initial analysis of these data indicated that individuals who received cooling in the IC and CC trials performed better physiologically than in the NC condition relative to measures of HR, skin temperature, core temperature, and heat storage. Four of the subjects completed at least 140 min work in the IC and CC conditions; therefore, additional statistical analysis was conducted on data up to this point comparing the IC and CC trials only.

This analysis indicated that the increase in T_{re} and T_{sk} temperatures observed over the first three work cycles were slightly higher during IC than during CC (Figs. 3 & 4). Although there were no differences in HR during the work cycles, the average HR during rest periods with CC was remarkedly lower than it was in IC (Fig. 5). Heat storage values were not statistically different between CC and IC during 140 min of intermittent work; however, the data suggest that physiological differences may exist because CC values tended to be consistently lower than CI measurements (Fig. 6). It should be noted that T_{sk}, T_{re}, and heat storage were lower at 140 min than at 100 min (Figs. 3, 4, & 6) because 140 min was in the middle of the third work cycle while 100 min was at the end of the second work cycle.

After 80-min intermittent exercise in the NC, IC, and CC condition, T_{sk} in the CC condition increased only 0.61°F (0.34°C) while those of the IC and NC increased 2.13°F and (1.12°C) and 2.68°F (1.49°C) respectively. Thus, using ambient air during work cycle lowered skin temperature more than the IC and NC conditions (Fig. 7).

As is indicated in Figure 8, sweat production (SP) rates were significantly lower for CC and IC than for NC, but the SP rate for CC was lower than for IC. The sweat evaporation (SE) rate for CC was higher than it was for IC and NC. Therefore, the SE percentage during the CC conduction was also significantly greater than it was for IC or NC.

During 50 min of continuous work in the AC condition, there was significantly less of an increase in heat storage (Fig. 9). Mean skin temperature (Fig. 10) was also observed to be significantly higher in the NC condition. AC had a significant effect on lowering TC ratings, which was evident even at the 10-

min point (Fig. 11). Sweat production rates were not different for AC and NC. However, there was a significant difference in SP and percent of SE (Fig. 12).

DISCUSSION

Three different cooling conditions (NC, IC, and CC) were examined during the intermittent work trials. The use of AC was compared with NC during continuous work. All cooling scenarios (AC, IC, CC) decreased thermal strain compared to no-cooling trials. Our findings, in general agreement with other work in the area of personal cooling (2, 3, 5, 7, 8, 9), complements and expands the knowledge base of microclimate cooling technology.

Significant differences were observed between CC and IC in skin temperature, heat storage, and sweat evaporation efficiency. Therefore, we successfully demonstrated that military personnel working in protective ensembles could wear ambient air units to cool the body and evaporate sweat.

The 8.5 lb burden experienced by subjects carrying the AC unit during work cycles might have counteracted some of the expected physiological and psychological benefits from AC (5). This energy cost may account for the fact that no statistically significant differences were seen for thermal comfort and ratings of perceived exertion between the IC and CC trials during intermittent work. Thermal comfort for AC was significantly better than it was for NC in the continuous work experiments. However, since only four subjects completed at least 140 min of intermittent work, there was limited data to analyze. These data may prove inadequate to reflect truly significant physiological effects. It is necessary to accumulate additional data by conducting more trials with volunteer subjects who finish four work/rest cycles with CC to provide a clearer picture of the perceived effect of CC. Furthermore, a less burdensome ambient air cooling unit and an optimized work/rest cycle should improve the application of ambient air cooling.

The filtered ambient air gained heat from the motor and control panel and increased inlet air temperature approximately 4-5°F (2-3°C). Therefore, the effect of convective cooling on skin temperature and the resulting thermal perception may have also been somewhat further compromised. Based on this consideration, ambient air cooling may work more efficiently in a mild environment (5) such as 80°F (26.7°C), 50% RH or below, where the inlet air temperature to the body would not exceed 85°F (29.4°C). A complete range on environmental temperatures should be evaluated in the laboratory to identify the optimal environmental working conditions for this ambient air cooling unit. Another possible approach may be to increase the air volume to 20 cfm to the body and 5 cfm to the face because most

subjects commented that air flow to the face was inadequate during work (8).

CONCLUSION

This beltpack ambient air cooling system has been shown to reduce thermal stress and improve personal comfort and likely mission efficiency in work tasks performed by military personel dressed in military CDE. Further improvements can be realized by reducing the total weight of the system and increasing its air flow. By introducing positive air pressure into the ambient air cooling system during work and rest cycles, breathing resistance should be decreased while protection from toxic substances is enhanced.

This ambient air cooling unit technology could possibly have promise in commercial or industrial nuclear, chemical, and toxic waste treatment and removal occupations when body protection is required.

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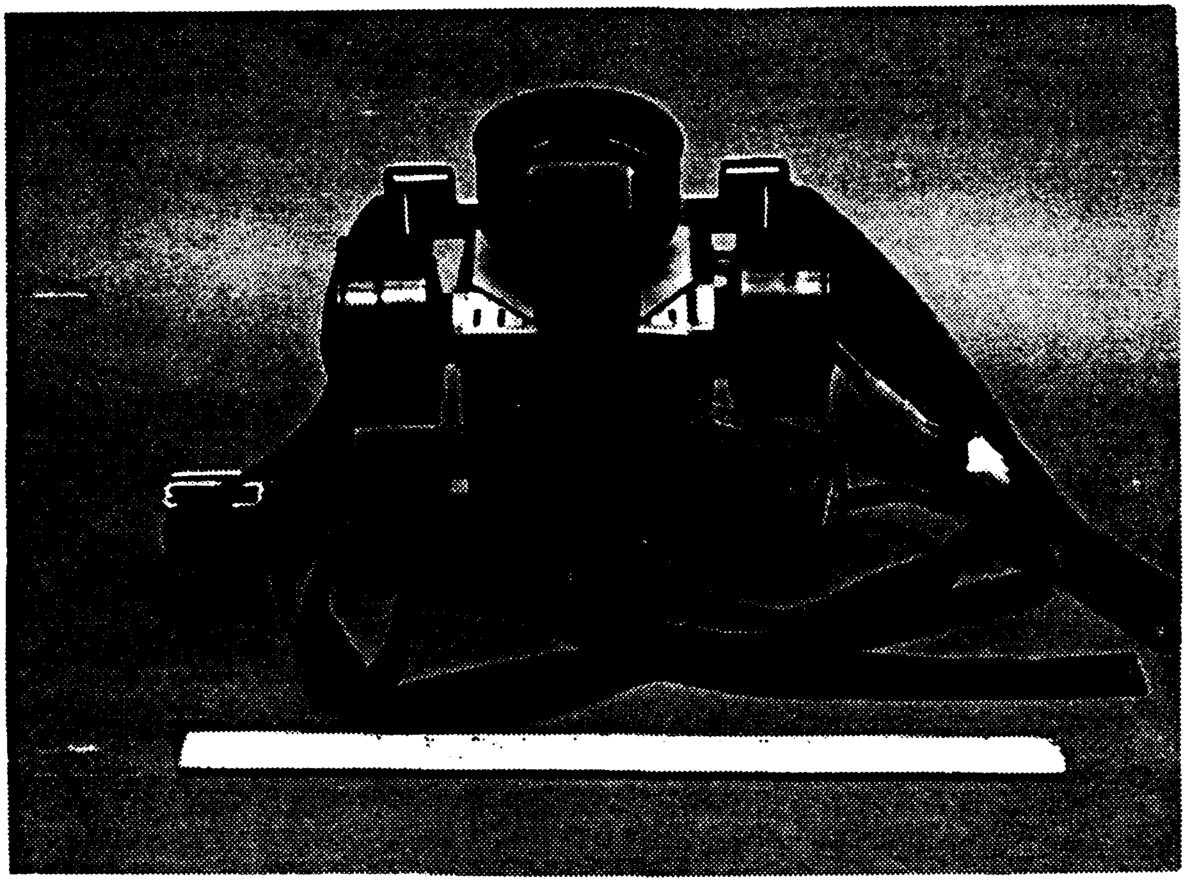

Figure 1. Ambient air cooling unit.

Figure 2. Unit ergonomically mounted on user's hips.

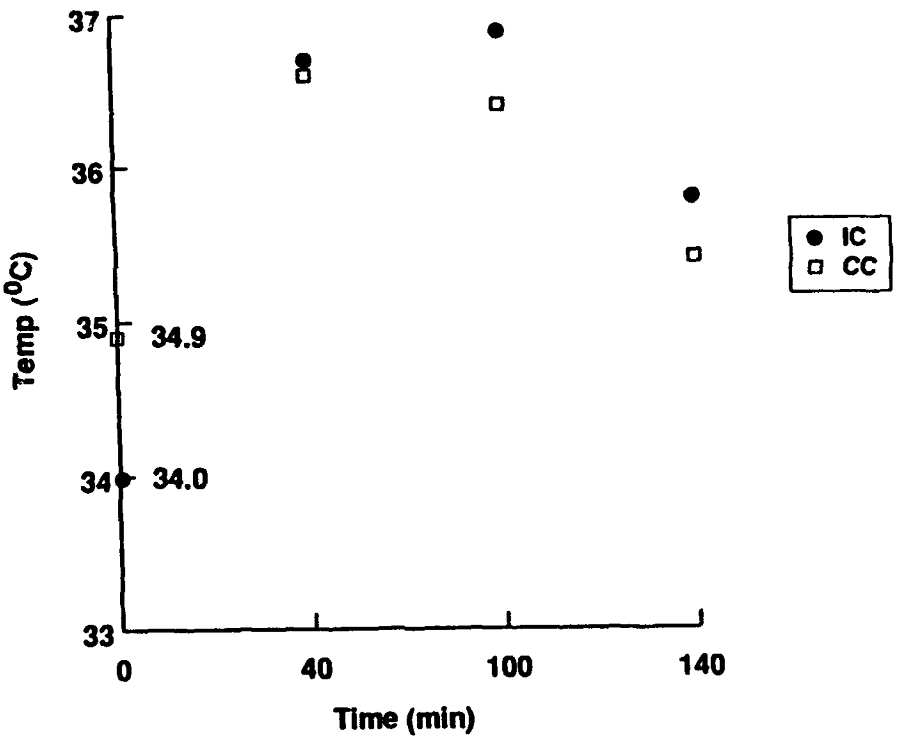

Figure 3. Mean skin temperature (CC and IC) before rest cycle.

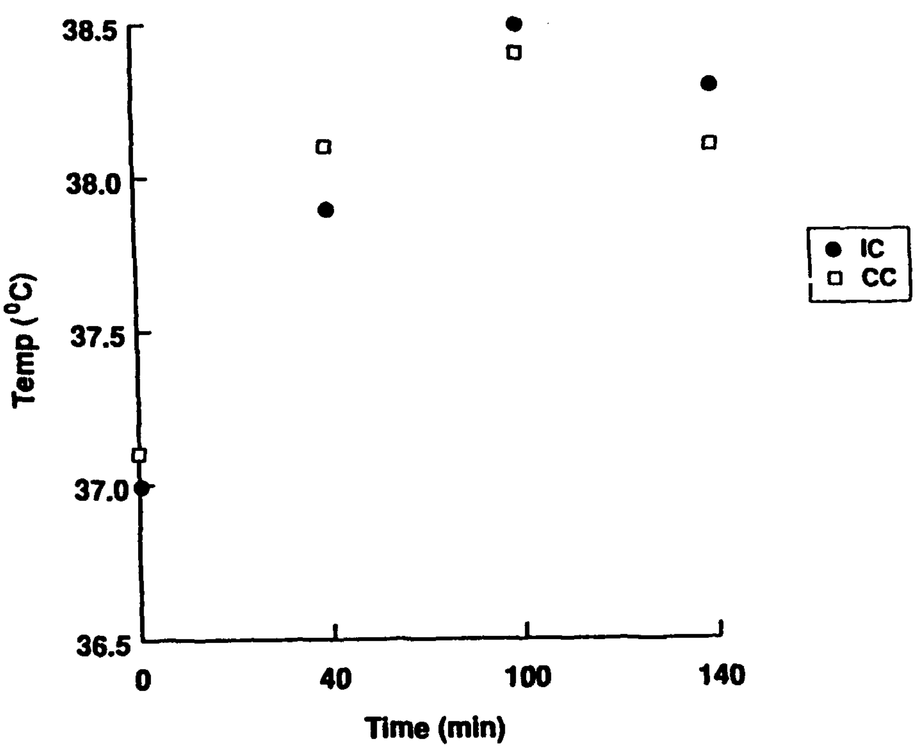

Figure 4. Core temperature before rest cycle.

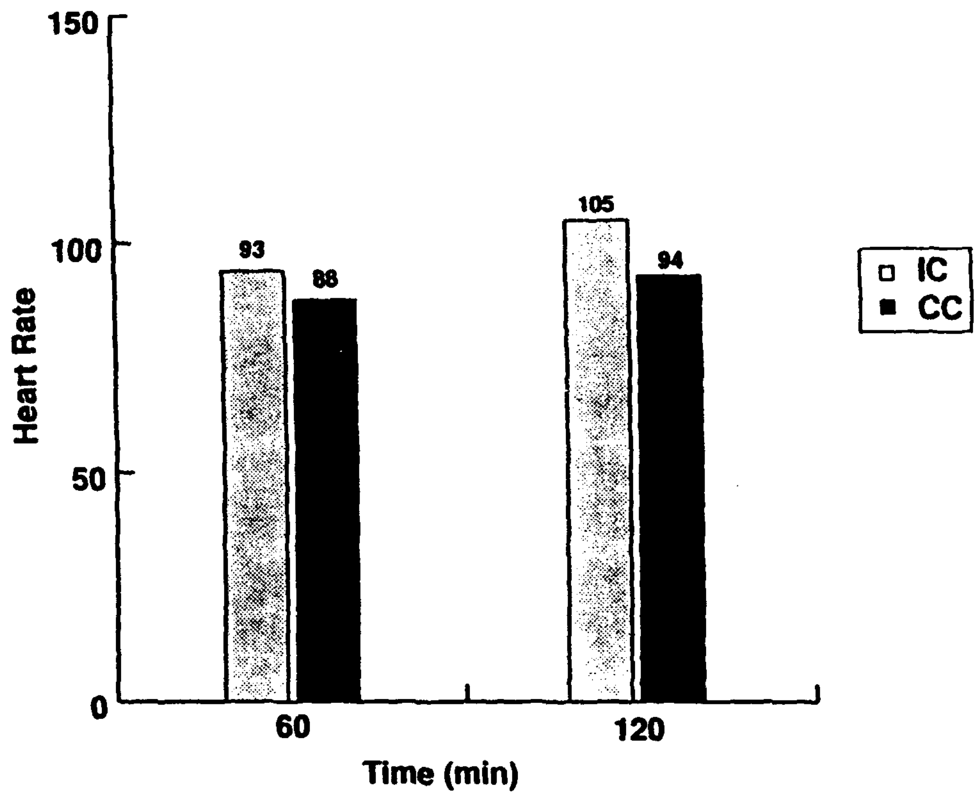

Figure 5. Heart rate (IC and CC) after rest cycle.

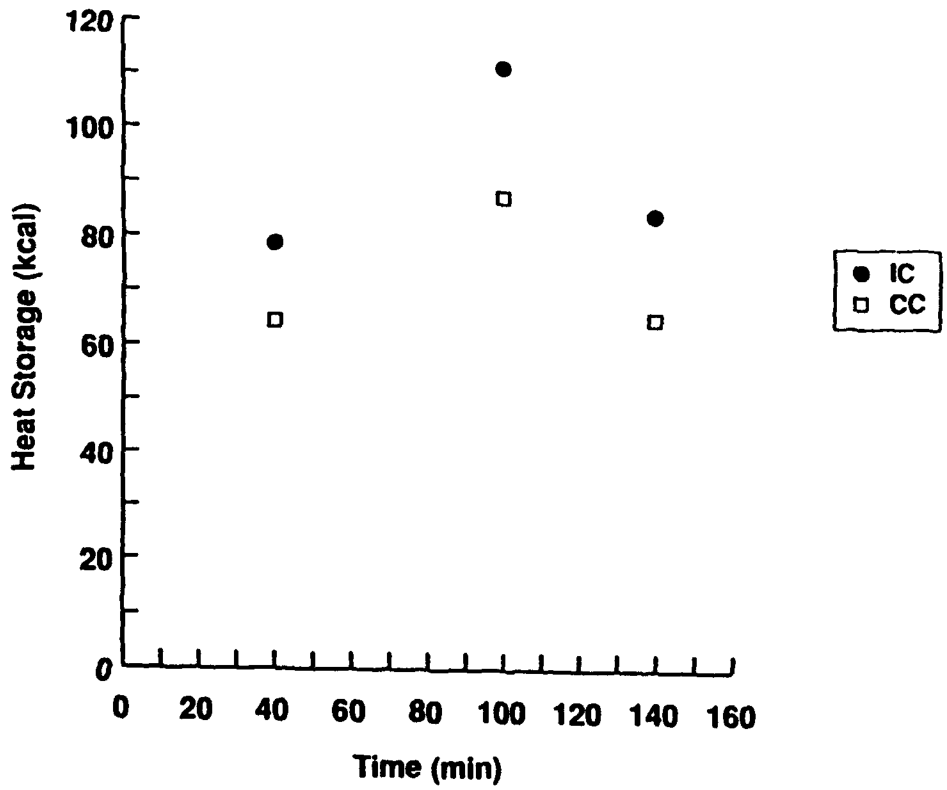

Figure 6. Heat storage during intermittent work.

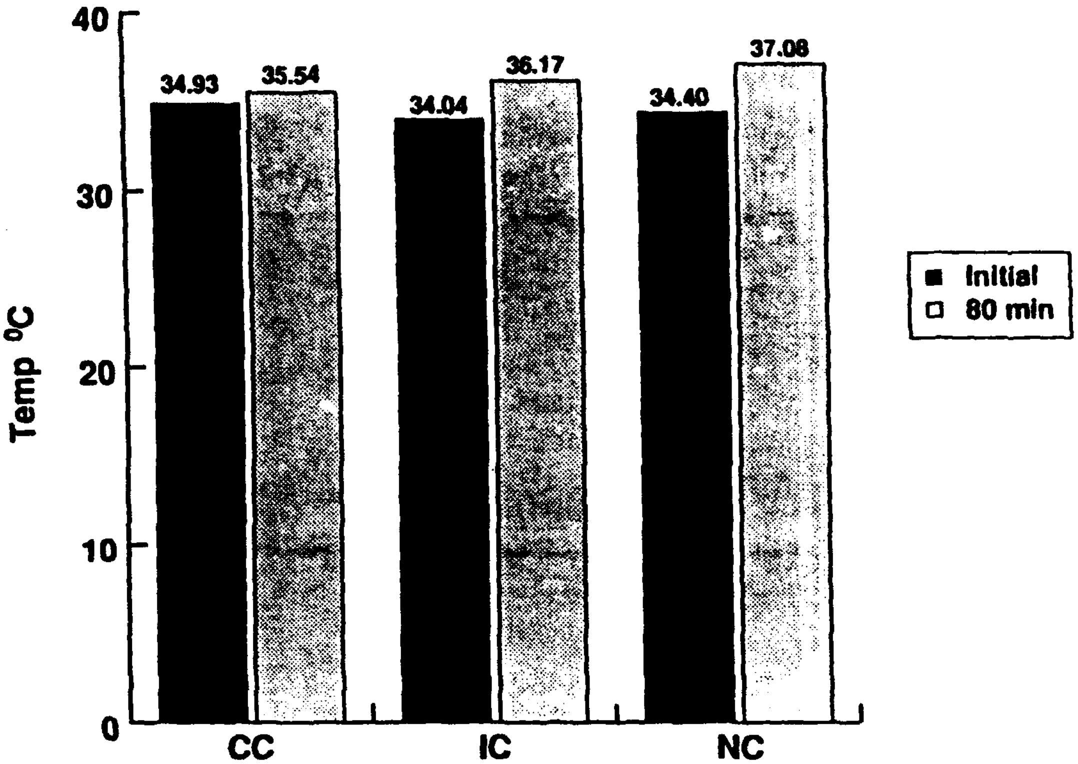

Figure 7. Initial skin temperature vs. 80 min.

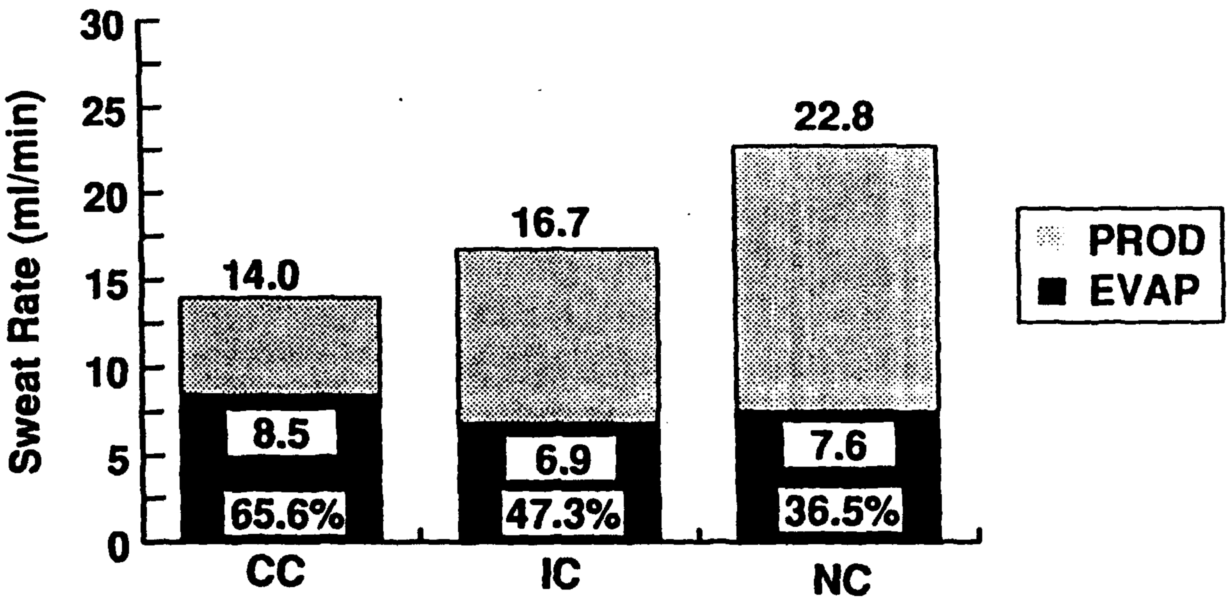

Figure 8. Sweat rate during intermittent work (%=EVAP/PROD).

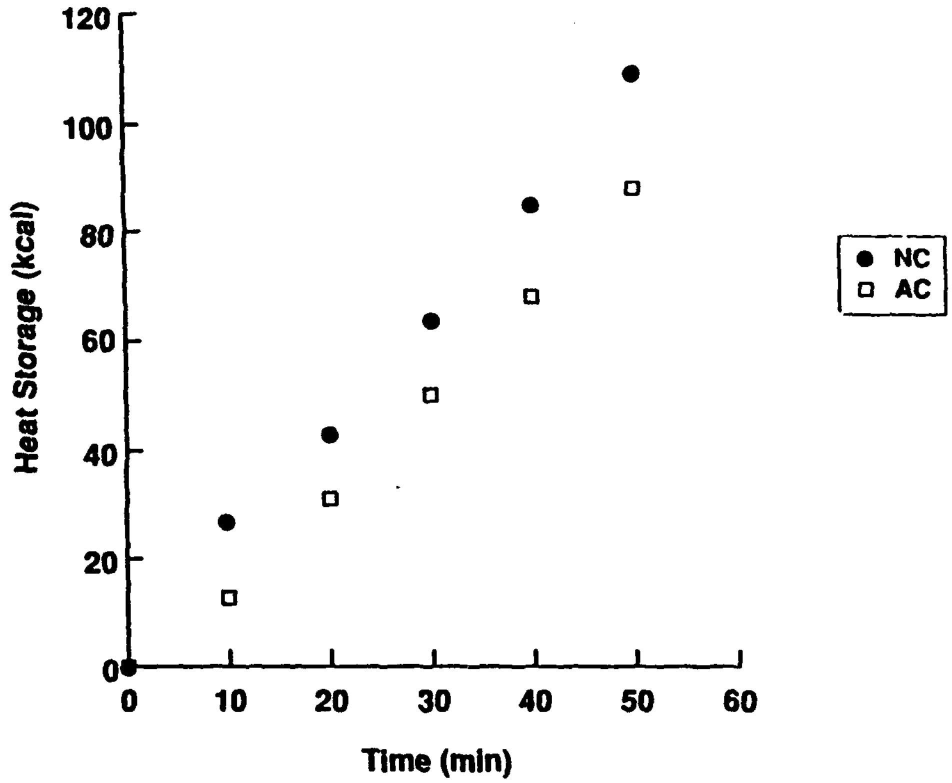

Figure 9. Heat storage during continuous work.

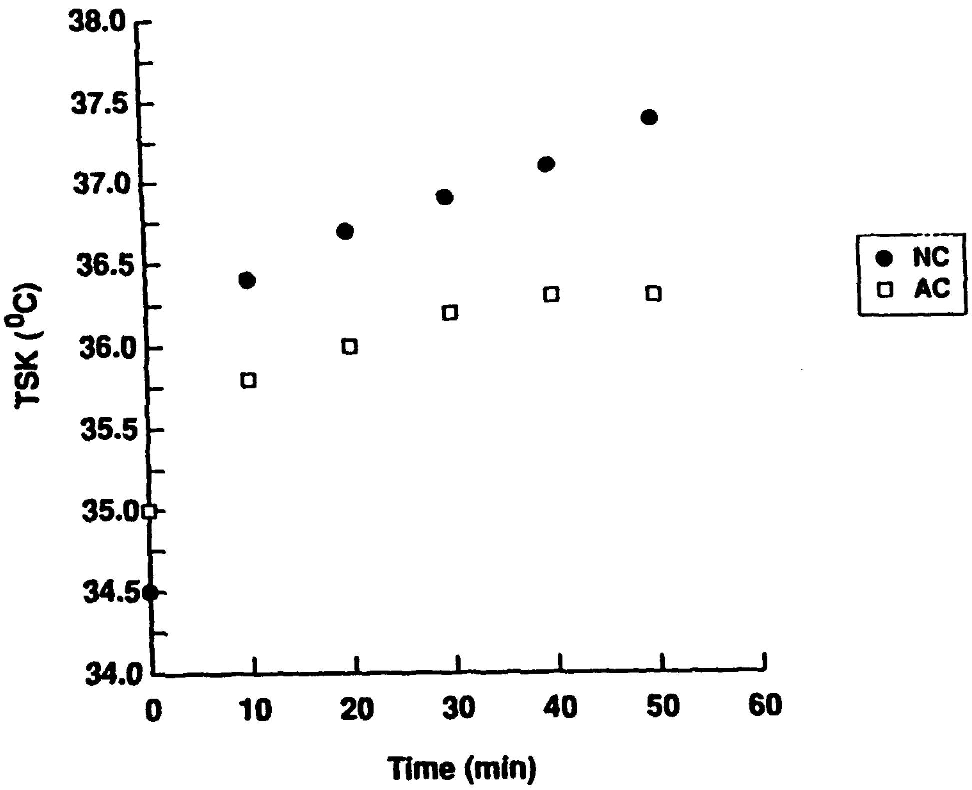

Figure 10. Mean skin temperature during continuous work.

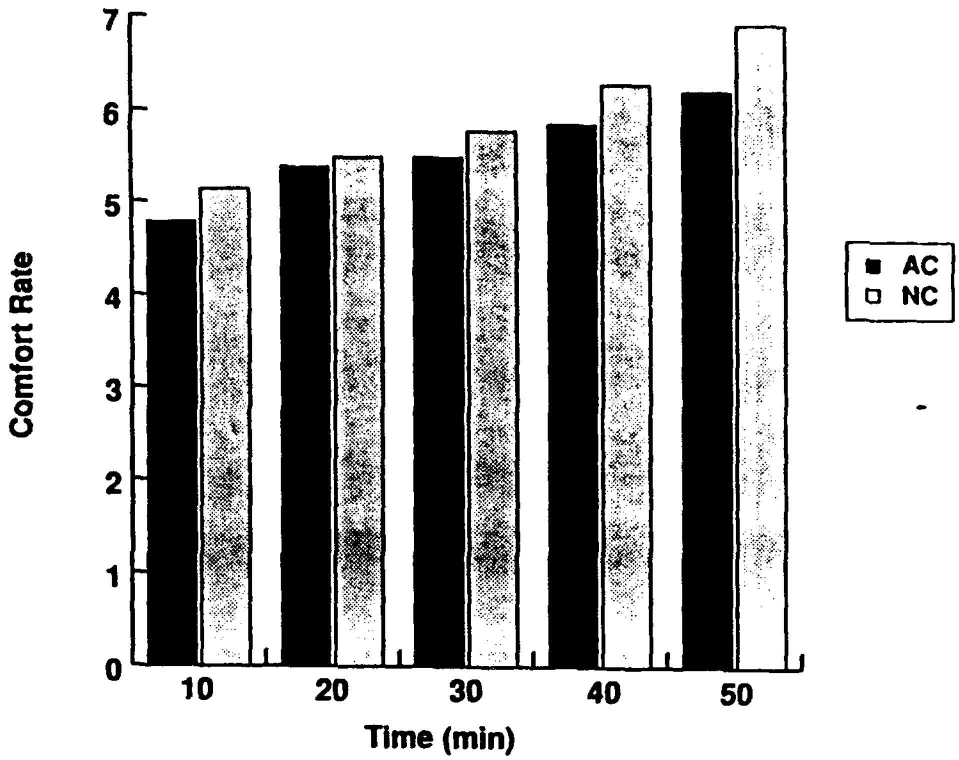

Figure 11. Thermal comfort rate during continuous work.

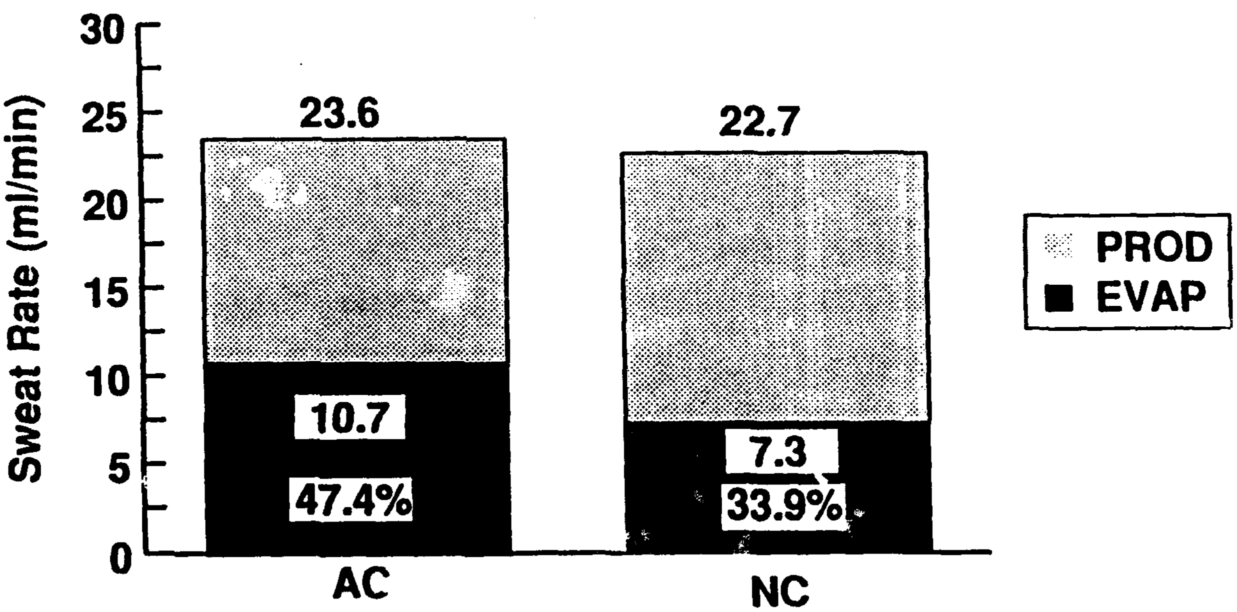

Figure 12. Sweat rate during continuous work (%=EVAP/PROD).